

The Direction of Fluid Dynamics for Liquid Propulsion at NASA Marshall Space Flight Center

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1. Abstract

Marshall Space Flight Center (MSFC) is the National Aeronautics and Space Administration (NASA)-designated center for the development of space launch systems. MSFC is particularly known for propulsion system development. Many engineering skills and technical disciplines are needed to accomplish this mission. This presentation will focus on the work of the Fluid Dynamics Branch (ER42). ER42 resides in the Propulsion Systems Department at MSFC. The branch is responsible for all aspects of the discipline of fluid dynamics applied to propulsion or propulsion-induced loads and environments. This work begins with design trades and parametric studies, and continues through development, risk assessment, anomaly investigation and resolution, and failure investigations. Applications include the propellant delivery system including the main propulsion system (MPS) and turbomachinery; combustion devices for liquid engines and solid rocket motors; coupled systems; and launch environments. An advantage of the branch is that it is neither analysis nor test centric, but discipline centric. Fluid dynamics assessments are made by analysis, from lumped parameter modeling through unsteady computational fluid dynamics (CFD); testing, which can be cold flow or hot fire; or a combination of analysis and testing. Integration of all discipline methods into one branch enables efficient and accurate support to the projects. To accomplish this work, the branch currently employs approximately fifty engineers divided into four teams – Propellant Delivery CFD, Combustion Driven Flows CFD, Unsteady and Experimental Flows, and Acoustics and Stability. This discussion will highlight some of the work performed in the branch and the direction in which the branch is headed.

1.1. Propellant Delivery System

The majority of ER42's work for MPS is conducted with CFD. For tanks, the branch performs analysis of propellant tank pressurization systems and the termination of the tank draining process. ER42 also conducts analysis of complex accelerated propellant tank sloshing to determine slosh modes and their respective frequencies, amplitudes and damping characteristics. Challenges associated with the future CFD simulation of the entire liquid propellant tank from tanking to end of mission, such as implementation of massively parallel gas-liquid interface tracking methods, are discussed. The branch conducts high-fidelity CFD simulations of liquid propellant feedlines to predict mean pressure drops through feedline components, flow uniformity due to bends and wakes, and unsteady pressure environments supporting the structural fatigue analysis of MPS components. In addition, the branch performs CFD simulations of valves to predict fluid flow patterns, mean pressure drops, and unsteady fluid environments for stationary as well as moving valves to support structural analysis of valve components. Today, the actuations of the valves are prescribed; future work is aimed at implementation of valve component force and friction models so that single and multiple degrees of valve motion may be predicted.

A significant focus area for the branch is turbomachinery. ER42 supports the design, development and certification of high-speed turbine and pump stages. The branch performs CFD analysis to produce environments, performance predictions, and blade loading. Time-accurate rotor-stator pressure time series are passed to structural dynamic finite element models (FEM) where forcing function-blade/vane resonance crossings are unavoidable. Rocket engine turbopumps frequently operate with minimal Net Positive Suction Head (NPSH) margin, so the discipline is often challenged by cavitation-induced oscillations. To this end, the branch utilizes highly instrumented pump waterflow tests to map both the steady and unsteady performance of inducers and impellers.

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ER42 is currently focusing on the rigorous extension of two-phase flow modeling capability. This capability, to be validated by waterflow test data, will allow the confident development of the complex on-blade oscillatory pressure fields resulting from cavitation-induced oscillations. Likewise, CFD and experiment together will optimize pump cavitation suppression designs, which is a major focus area currently within the rocket engine industry. The branch continues to penetrate the system damping offered by pump blades vibrating within moving propellants. These blade immersed damping features should offer substantial relief to high cycle fatigue issues related to cavitation oscillation or rotor-stator induced loadings.

1.2. Combustion Devices

ER42 is responsible for the fluid dynamics areas required to support design and development of liquid rocket engine thrust chamber assemblies (TCAs) including propellant manifolds, injectors, combustion chambers, and nozzles. A current focus area for the branch is combustion stability. The stability assessment has historically been accomplished with a combination of engineering tools and hot-fire testing. Because of the low geometric fidelity and the empirical nature of the inputs, the engineering tools lack robust *a priori* predictive capability for new or innovative designs, and often require significant anchoring with test data well into the engine development program. Recent and on-going branch advancements are refining the stability analysis approaches and correspondingly improving confidence in the stability assessments. FEM has been used for more accurate modal analysis of complex geometries. Additionally, engineering tools are being improved with the incorporation of more physics-based inputs such as time lag, energy release profile, and mixing efficiency extracted from detailed CFD simulations. ER42 is also working to refine how combustion stability is empirically assessed through engine test data. Spontaneous and dynamic stability rating methods are being updated by using statistical approaches to better characterize the measured combustion dynamic pressures; thus, assessing combustion stability at a given operating condition with greater accuracy.

1.3. Launch Environments

Launch environments are a particularly busy application area for the branch, and include overpressure (OP), acoustics, and debris transport. The OP phenomenon is a transient at liftoff resulting from fluid compression of the rapidly accelerating plume gas into a confined, usually quiescent, region, the subsequent rarefaction, and the propagation from the exhaust trench and duct holes. The potentially high amplitude, unsteady fluid dynamic perturbations can adversely affect the vehicle and surrounding structure. Early OP predictions are made using an analytical approach. CFD has recently shown to represent overpressure very accurately without the inclusion of water suppression effects. The current goal is to improve the CFD capabilities to include the modeling of water suppression systems, the multiphase booster effluent with alumina particles, and to capture higher frequency spectral content. Liftoff noise is generated by the mixing of rocket exhaust flow with the surrounding atmosphere and its interactions with launch complex structures. ER42 initially creates liftoff predictions by leveraging general acoustic theory and empirical data inputs. Prediction of acoustic environments with CFD is challenging, as waves must be propagated across distances on the order of hundreds of meters. ER42 has begun implementing sub-domain methods aimed at providing a predictive capability for the low-frequency portion of the launch pad acoustic environment. After the liftoff environment is released, ER42 validates the environment by subscale testing, where the full-scale noises are captured in a subscale configuration, and the measured environments are scaled to full-scale environments. After testing, the data is analyzed and compared to initial predictions. Final recommendations based on scale model testing could include updating the environment and implementing water sound suppression systems.

1.4. Summary

The applications discussed in this presentation are the tip of the iceberg of the work required and conducted by the Fluid Dynamics Branch at MSFC to support propulsion development. It does, however, provide an appreciation of the depth and breadth of the branch applications, its current approaches, and where the branch is working to improve the state of its practice.